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6. AUTHORS Rodrigo Amezcua Correa, Lawrence Shah, Martin Richardson, Axel Schulzgen	5d. PROJECT NUMBER
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14. ABSTRACT
Monolithic fiber lasers systems are highly desirable for defense and industrial applications due to their excellent beam quality, high efficiency, ruggedness, and compactness. Photonic crystal fibers (PCF) with large mode field diameters are a promising technology for further power scaling of current high power fiber lasers and amplifiers. However, the integration of PCF's into efficient and reliable all-fiber laser systems is a significant challenge. Firstly, high-performance PCF required for high power operation are difficult to manufacture. Secondly, PCF

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All Fiber Devices, Fiber Post-processing, Fiber optics amplifiers and oscillators, Photonic crystal fibers

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Report Title

Final Report: Advanced Splicing and High-Resolution Imaging Facility for High Power PCF Laser Fabrication

ABSTRACT

Monolithic fiber lasers systems are highly desirable for defense and industrial applications due to their excellent beam quality, high efficiency, ruggedness, and compactness. Photonic crystal fibers (PCF) with large mode field diameters are a promising technology for further power scaling of current high power fiber lasers and amplifiers. However, the integration of PCF's into efficient and reliable all-fiber laser systems is a significant challenge. Firstly, high-performance PCF required for high power operation are difficult to manufacture. Secondly, PCF splicing and fused components processing (pump combiners, mode adaptors, output couplers, and end caps) require non-conventional splicing technologies. High power fiber laser development for the nation's high energy laser program, is a core component of the Townes Laser Institute (TLI). Thus, in this DURIP the requested funding will provide the TLI with key equipment to characterize, process, and integrate PCF's into all-fiber high power laser systems. Specifically, a tabletop scanning electron microscope (SEM) and a CO2 laser splicing station are requested for this facility. These instruments will add to our current fiber processing and characterization capabilities acquired under several DoD contracts.

Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

Received Paper

TOTAL:

Number of Papers published in peer-reviewed journals:

(b) Papers published in non-peer-reviewed journals (N/A for none)

Received Paper

TOTAL:

Number of Papers published in non peer-reviewed journals:

(c) Presentations

Number of Presentations: 0.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received Paper

TOTAL:

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received Paper

TOTAL:

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):

(d) Manuscripts

Received Paper

TOTAL:

Number of Manuscripts:

Books

Received Book

TOTAL:

Received Book Chapter

TOTAL:

Patents Submitted

Patents Awarded

Awards

Graduate Students

NAME	PERCENT_SUPPORTED	Discipline
Amado Velazquez	0.00	
Amy Van Newkirk	0.00	
Alex Sincore	0.00	
FTE Equivalent:	**0.00**	
Total Number:	**3**	

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
Enrique Lopez	0.00
FTE Equivalent:	**0.00**
Total Number:	**1**

Names of Faculty Supported

NAME	PERCENT_SUPPORTED	National Academy Member
Rodrigo Amezcua Correa	0.00	
Axel Schulzgen	0.00	No
Martin Richardson	0.00	No
Lawrence Shah	0.00	
FTE Equivalent:	**0.00**	
Total Number:	**4**	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED

FTE Equivalent:
Total Number:

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: 0.00

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:...... 0.00

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):...... 0.00

Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense 0.00

The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields: 0.00

Names of Personnel receiving masters degrees

NAME
Alex Sincore
Total Number: 1

Names of personnel receiving PHDs

NAME

Total Number:

Names of other research staff

NAME	PERCENT_SUPPORTED

FTE Equivalent:
Total Number:

Sub Contractors (DD882)

Inventions (DD882)

Scientific Progress

See Attachment

Technology Transfer

No technology transfers are reported during this project

1) **Period covered by report**: August 01, 2013 to July 31, 2014
2) **Proposal Title**: ADVANCED SPLICING AND HIGH-RESOLUTION IMAGING FACILITY FOR HIGH POWER PCF LASER FABRICATION
3) **Proposal Number**: 63541ELRIP
4) **Agency Grant Number:** W911NF-13-1-0283
5) **Author of Report:** Rodrigo Amezcua-Correa, Lawrence Shah
6) **Performing Organization Name and Address:**
   CREOL – the College of Optics and Photonics, University of Central Florida. 4000 Central Florida Blvd. Orlando, FL 32816-2700.

DURIP - ADVANCED SPLICING AND HIGH-RESOLUTION IMAGING FACILITY FOR HIGH POWER PCF LASER FABRICATION

Final Report

by: Rodrigo Amezcua Correa (PI)
Lawrence Shah (co-PI)
Axel Schülzgen (co-PI)
Martin Richardson (co-PI)

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CREOL, College of Optics & Photonics
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ABSTRACT (original proposal, September 2012)

Monolithic fiber lasers systems are highly desirable for defense and industrial applications due to their excellent beam quality, high efficiency, ruggedness, and compactness. Photonic crystal fibers (PCF) with large mode field diameters are a promising technology for further power scaling of current high power fiber lasers and amplifiers. However, the integration of PCF's into efficient and reliable all-fiber laser systems is a significant challenge. Firstly, high-performance PCF required for high power operation are difficult to manufacture. Secondly, PCF splicing and fused components processing (pump combiners, mode adaptors, output couplers, and end caps) require non-conventional splicing technologies. High power fiber laser development for the nation's high energy laser program, is a core component of the Townes Laser Institute (TLI). Thus, in this DURIP the requested funding will provide the TLI with key equipment to characterize, process, and integrate PCF's into all-fiber high power laser systems. Specifically, a tabletop scanning electron microscope (SEM) and a CO_2 laser splicing station are requested for this facility. These instruments will add to our current fiber processing and characterization capabilities acquired under several DoD contracts.

Keywords: All fiber devices, fiber post-processing, fiber optics amplifiers and oscillators, photonic crystal fiber

Contents

The Report Documentation Page

(1) Submissions or publications under ARO sponsorship during this reporting period. List the title of each and give the total number for each of the following categories:

(a) Papers published in peer-reviewed journals
N/A

(b) Papers published in non-peer-reviewed journals
N/A

(b) Presentations:
N/A

i. Presentations at meetings, but not published in Conference Proceedings

ii. Non-Peer-Reviewed Conference Proceeding publications (other than abstracts): 3

iii. Peer-Reviewed Conference Proceeding publications (other than abstracts): 3

(d) Manuscripts:
N/A

(e) Books
N/A

(f) Honor and Awards: 4

1. 2013 SPIE Harold E Edgerton Award, awarded to Martin Richardson
1. 2013 Docteur Honoris Causa Université de Bordeaux awarded to Martin Richardson
2. 2014 Jefferson Fellowship awarded to Martin Richardson
3. 2014 Fellow of the American Physical Society (APS), Martin Richardson
4. 2013 Fellow of Institute of Electrical, Electronic Engineers (IEE), Martin Richardson

(g) Title of Patents Disclosed during the reporting period
N/A

(h) Patents Awarded during the reporting period
N/A

(2) Student/Supported Personnel Metrics for this Reporting Period

(a) Graduate Students: 3

1. Amado Velazquez
2. Alex Sincore
3. Amy Van Newkirk

(b) Post Doctorates: 1

1. Enrique Lopez

(c) Faculty: 4

1. Rodrigo Amezcua-Correa
2. Lawrence Shah
3. Martin Richardson
4. Axel Schülzgen

(d) Undergraduate Students

N/A

(e) Graduating Undergraduate Metrics (funded by this agreement and graduating during this reporting period):

N/A

i. Number who graduated during this period:

N/A

ii. Number who graduated during this period with a degree in science, mathematics, engineering, or technology fields:

N/A

iii. Number who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields

N/A

iv. Number who achieved a 3.5 GPA to 4.0 (4.0 max scale)

N/A

v. Number funded by a DoD funded Center of Excellence grant for Education, Research and Engineering

N/A

vi. Number who intend to work for the Department of Defense

N/A

vii. Number who will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields

N/A

(f) Masters Degrees Awarded: 1

1. Alex Sincore

(g) Ph.D.s Awarded:

N/A

(h) Other Research staff:

N/A

(3) "*Technology* transfer"

N/A

(4) Scientific Progress and Accomplishments

See page

(5) "Copies of technical reports"

N/A

Scientific Progress and Accomplishments

1. Summary

This grant enabled the purchase of critical equipment for fiber laser component development. This grant builds upon DoD support in other programs, such as the ARO/JTO funded MRI on "Fiber Laser Light Engines - A New Platform to Collectively Address Power-limiting Constraints" (contract #: W911NF-12-1-0450) and AFSOR DURIP grant "MCVD lathe system for fiber preform fabrication" (contract #FA23861313019). In addition to related research to overcome the current limitation in power scaling of fiber lasers due to thermal mode instabilities, this new CO_2 laser tapering has enabled several significant achievements in advanced optical fiber devices.

During this project we have developed processes and protocols for the fabrication of all-fiber pump combiners and have successfully demonstrated advanced all-fiber mode converters. In the process, several important observations have been made which will guide further research to increase the functionality of all-fiber devices. Furthermore, during this project we have established a new dedicated laboratory for fiber component development, which in addition to the CO_2 laser splicer, it includes microscopes, a fiber bundle assembly rig, and fiber polishing and cleaving machines.

The awarded budget and the final purchase details are summarized in Table 1. The ARO DURIP award was $120,000, whereas the final equipment cost was $130,500.

Table 1: Purchasing

Proposed Equipment	Vendor	Projected Cost	Final Costs
LAZERMaster LZM-100 $C0_2$ Laser Splicing System. System includes: Rotation stages for PCF and PM fiber aligning End view observation for camera for end cap splicing	**AFL global** www.aflglobal.com	$170,000	$130,500

2. Description of Equipment

In the original DURIP proposal, we proposed the purchase of two important instruments for advanced optical fiber processing, reliable fiber component development, and accurate fiber characterization of PCF for high power applications. The two instruments originally requested were:

- AFL's LAZERMaster LZM-100 C02 Laser Splicing Station
- Hitachi's TM-3000 Tabletop Scanning Electron Microscope (SEM)

With this ARO DURIP we have acquired an AFL's LZM-100 CO2 laser splicing and tapering station. Funding for the SEM microscope was not awarded. AFL's LZM-100 LAZERMaster is a new generation glass processing and splicing system that uses a CO_2 laser as the heat source

(rather than electrode, filaments, or flame) providing precise heat localization and control, high process purity, and ensuring repeatable performance and low maintenance. Splicing or adiabatic tapering can be performed with fiber diameters of more than 2.5 mm, Fig. 1 shows an image of the tapering station and the tapering control software. The system includes an end-view imaging system for fully automated rotational alignment and splicing of polarization maintaining fibers and end caps. This splicing station is capable of PCF splicing and processing, end cap splicing and can be used to fabricate pump combiners, fiber tapers, mode field adaptors and fiber bundles.

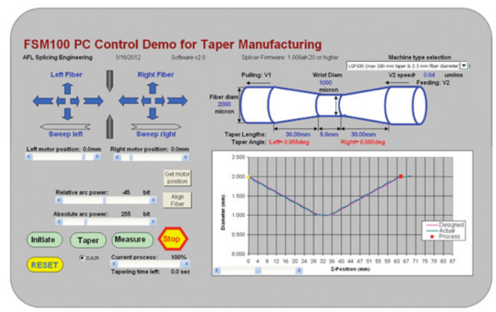

Figure 1. AFL's LAZERMaster LZM-100 $C0_2$ and tapering control software.

Key features of the LAZERMaster LZM-100 $C0_2$ laser splicing station:

- CO_2 laser provides extremely stable operation and eliminates electrode or filament maintenance
- Laser beam diameter control and focusing for precise temperature localization
- > 2.5 mm maximum fiber diameter
- PCFs can be spliced with no air hole collapse and low-loss
- Capability of uniformly collapsing PCF air hole microstructure
- Ability to splice largely dissimilar fiber diameters surpasses capabilities of all existing splice technologies
- Capabilities for splicing end caps
- Capabilities for fabricating pump combiners, tapes, fiber bundles, etc
- Extremely high splice strengths are achievable
- High repeatability and stability for large scale production
- Scalable to much larger fibers by increasing laser power
- Long travel / high resolution Z motion for long adiabatic tapers
- Automatic operation by on-board LZM-100 splicer firmware, manual operation or operation by computer

3. All-Fiber Laser Components

During this project we have established a dedicated laboratory for the fabrication all-fiber components, such as pump combiners and mode convertors for high power fiber laser applications. The new laboratory houses the CO_2 splicer obtained with ARO DURIP grant, one fiber pump combiner fabrication rig, one Vytran fiber cleaver, a fiber polisher, microscopes and equipment required for fiber post-processing. A picture of the laboratory is shown in Fig. 2.

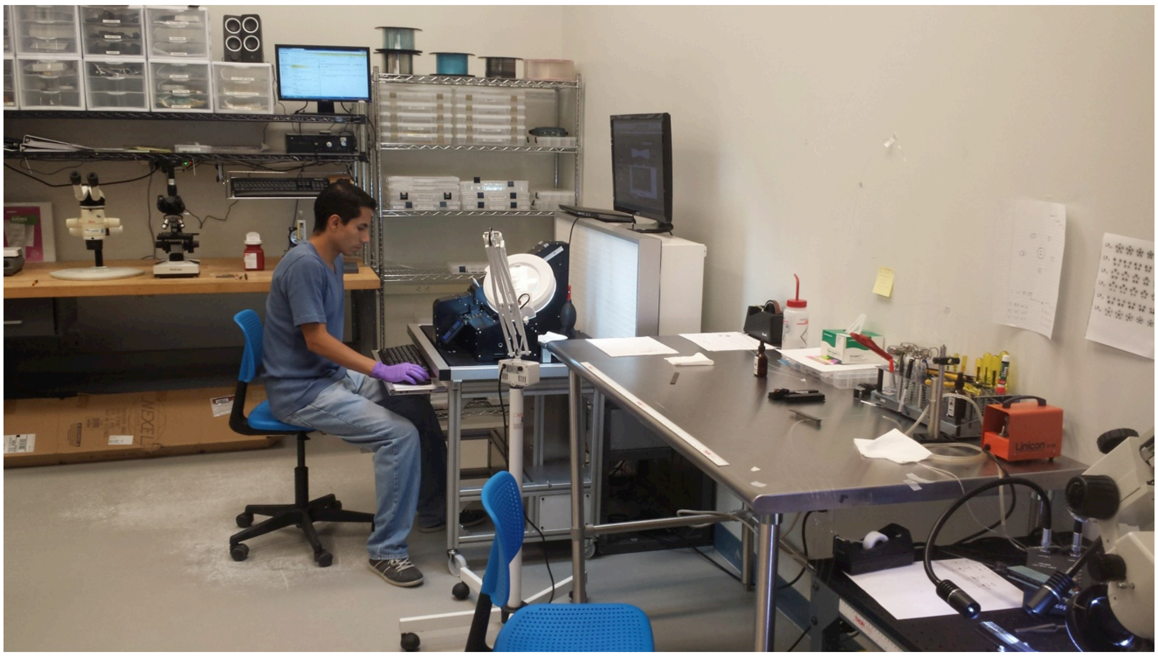

Figure 2. PhD student Amado Velazquez fabricating fiber pump combiners with the AFL's LAZERMaster LZM-100 $C0_2$ Laser Splicing Station.

3.1. Fiber Combiners

Since the acquisition of the AFL splicer we have developed fiber bundle fabrication processes and have demonstrated low-loss fiber combiners. Our set-up for fabricating a fiber bundle in a Fluorine doped capillary is shown Fig. 3. The set-up greatly facilitates the bundle fabrication process, reducing contamination, fiber twisting and other factors that result in losses in the final fiber combiner. Multimode to single mode fiber combiners were developed and characterized, so far we have successfully fabricated of 3, 6, 8 and 10 fiber combiners. These fiber combiners efficiently couple light from a number of single mode fibers into a large multimode fiber. Fig 4. shows the cleaved waist of fused tapered fiber combiners with 3, 6, 8 and 10, respectively. In the image the dark region corresponds to the low refractive index fluorine doped material. For the combiner fabrication, a bundle of single mode fibers are inserted into a F doped capillary, the fiber capillary is fused together and tapered by a factor > 5. The core at the taper waist is formed by the tapered input fibers, while the surrounding fluorine doped capillary forms the multimode waveguide cladding.

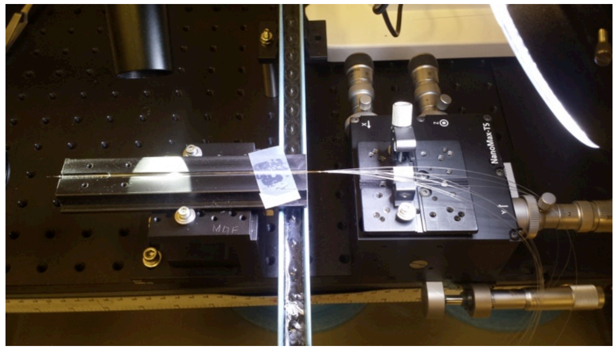

Figure 3. Image of a 10 fibers bundle inside a fluorine doped capillary.

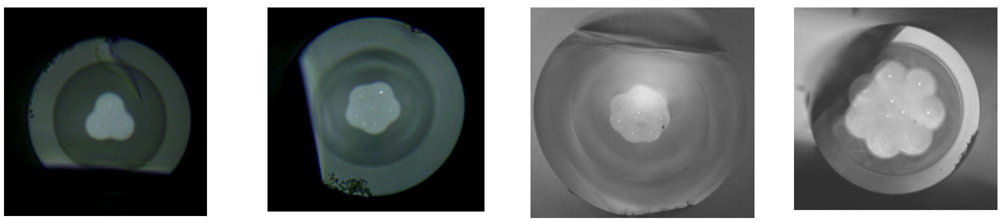

Figure 4. Claeved waist of fused tapered 3, 6, 8 and 10 fiber combiners. The fibers used for the bundle fabrication are single mode fibers.

Figure 5, presents an example of a fabricated tapered fiber combiner of eight input fibers. Cross-section images at different positions along the length of the tapered transition from an initial 1100 um outer diameter to a tapered diameter of 680 um, are shown at the same scale.

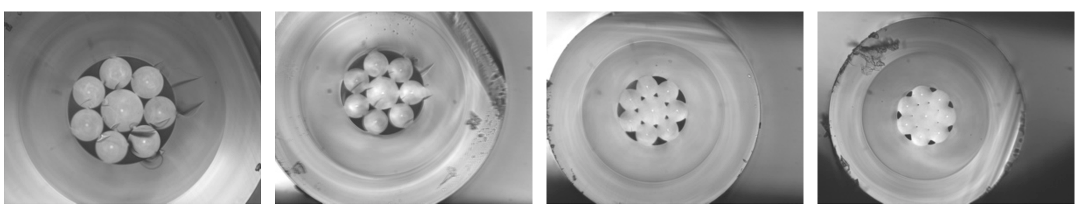

Figure 5. Cross-section images at different points along the length of an 8 fibers tapered fiber bundle transition, the images are taken at the same scale. The bundle outer diameters are, from left to right: 1100 um, 870 um, 750 um and 680 um.

3.2 All-Fiber Mode Convertors

All-fiber mode convertors combine a bundle of dissimilar fibers within a low refractive index glass capillary by adiabatically tapering to a smaller diameter, giving place to a multimode waveguide at the taper end as depicted in Fig. 6. The use of dissimilar fibers breaks the mode degeneracy along the taper and prevents mode mixing, allowing the fundamental mode of each input fiber to evolve into one mode of the output multimode fiber modes. Three fibers mode convertors which excite the LP01 and LP11a,b modes have been successfully demonstrated by

other research groups[1]. During this project we have developed mode convertors with mode selectivity for 6 spatial modes (first 4 LP modes). The mode convertor is achieved using for its fabrication six fibers inside a low refractive index capillary where four dissimilar core fibers were employed in order to individually excite the LP01, LP11a,b , LP21a,b and LP02 modes. Furthermore, we demonstrate that the use of graded index fibers for device fabrication eases the length requirements of the adiabatic tapered transition and could enable scaling to mode converters supporting larger number of modes.

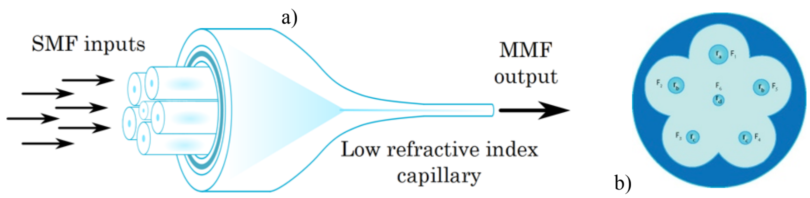

Figure 6. Illustration of an all fiber 6 mode convertor: a) capillary filled with six different fibers, and b) transversal illustration of the multimode fiber output.

For device fabrication, a fluorine doped capillary with Dn = - 9x10^{-3} was used. Six fibers were inserted in the capillary and subsequently tapered by a factor of ~11 of its original diameter using the CO_2 laser tapering station. The final core diameter is ~ 29 um. In the case of the PL using six step index fibers, four fibers with distinct core sizes and Dn = 5x10^{-3} were employed to achieve mode selectivity: one 15 μm for LP01, two 10 μm for the LP11a,b, two 8 μm for the LP21a,b, and one 5 μm for the LP02. For a close comparison, similar core sizes were selected for the mode converter fabricated employing six graded index fibers: 15 μm for LP01, two 13 μm for the LP11a,b, two 10 μm for the LP21a,b, and one 6 μm LP02. The same design and capillary was used for both lantern types. All fibers have been fabricated in our fiber fabrication facility. In order to ensure an adiabatic transition, numerical simulations using a fast Fourier transform beam propagation method and modal analysis guided the targeted taper transition of the devices. After fabrication, the end facets are cleaved for the purpose of characterization and measurement of insertion loss. Pictures of the end-face of the step index and graded index lanterns are shown in Fig. 7.

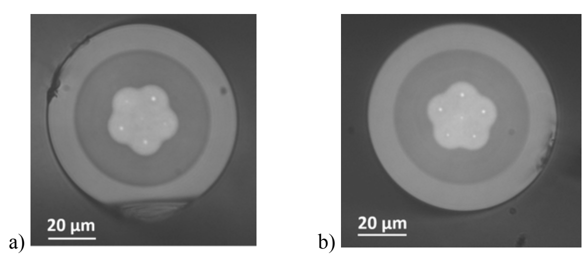

Figure 7. Microscope images of the fabricated six spatial mode convertors using a) step index and b) graded index fibers.

[1] Sergio G. Leon-Saval, Nicolas K. Fontaine, Joel R. Salazar-Gil, Burcu Ercan, Roland Ryf, and Joss Bland-Hawthorn, "Mode-selective photonic lanterns for space-division multiplexing," Optics Express, Vol. 22, Issue 1, pp. 1036-1044 (2014).
S. Yerolatsitis, I. Gris-Sánchez, and T. A. Birks, *"Adiabatically-tapered fiber mode multiplexers,"* Optics Express, Vol. 22, Issue 1, pp. 608-617 (2014).

Generally speaking, graded index fibers allow for larger core sizes with smaller effective mode areas for the LP_{01} mode compared to step index fibers. Therefore the use of graded index fibers for PL fabrication reduces the mode coupling and reduces the length required to achieve an adiabatic transition. Note that increasing the number of modes increases the required tapering length and therefore the fabrication complexity. In our experiments the use of graded-index fibers for the mode convertor fabrication allows for a reduction in the taper transition length by a factor of ~1.5 compared to the mode convertor fabricated using step-index fibers. Characterization of the mode convertors was performed using a superluminescent diode centered at 1550 nm. Imaging of the near field intensity patterns was carried out by employing an infrared camera (Xenics, XEVA-1.7-320) focusing the image through a 20x microscope objective. The output signals of the mode converters are presented in Fig. 8 and 9, showing the near field modal patterns, and intensity profile for step and graded index mode converters, respectively. Each input fiber maps to one mode at the output of the mode convertor. The observed pentagonal shape of the mode patterns is due to the geometry of the core generated when the capillary collapses and the air gaps between fibers are filled. Our experimental results are in good agreement with the prediction obtained by numerical simulations.

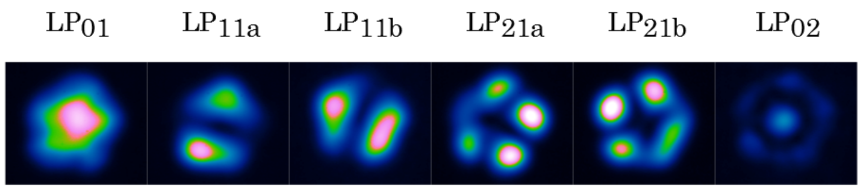

Figure. 8. Mode profiles of the mode converter fabricated with step index fibers.

Analyzing the intensity distribution of mode profiles at the output of the lantern, it can be observed that the minimum between peaks is almost negligible, reaching maximum values of 7 % for the LP_{02}. Usual insertion losses for the lantern are in the range of 0.7 and 0.6 dB for all modes.

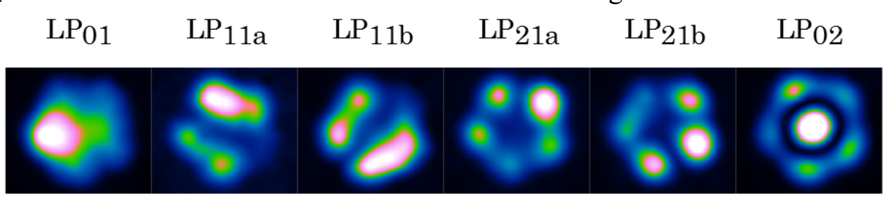

Figure. 9. Mode profiles of the mode converter fabricated with graded index fibers.

4. Future Fiber Component Development

- Fabrication of high power fiber pump combiners using 105 um core, 125 um cladding fibers with NA = 0.22
- Development of mode convertors for high order modes
- Development of high power wavelength division multiplexers (WDMs)
- Large pitch PCF end-caps
- PCF end face collapsing and splicing